9.5A ATMOSPHERIC FLOW DECOUPLING AND ITS EFFECTS ON URBAN PLUME DISPERSION

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1. INTRODUCTION

An understanding of plume dispersion in urban environments adequate for the reliable prediction of plume behavior remains elusive. These environments are characterized by their complexity. Urban canopies (Oke 1988; Grimmond and Oke 2002) feature irregularly differential heights, widths, geometries, and building aspect ratios, varying traffic patterns, differential surface insolation, and possibly irregular street grid layouts. Additional complications arise when the effects of thermal regime and terrain (e.g. topographic variation, land-sea breezes) are included. Add in mesoscale and synoptic variations, with continually varying wind speed and wind direction in the approach flow, and the uncertainty with regard to plume release location in a real emergency, and the scale of the problem becomes apparent. All of these factors will influence the flow field and plume dispersion pattern. Overall reviews of the effort to achieve this understanding have been presented by Britter and Hanna (2003) and Vardoulakis et al. (2003).

In spite of considerable effort to better understand and predict urban plume dispersion, a great deal of uncertainty remains. There has been a relative paucity of experimental laboratory or field studies that can be used to refine the models or test their accuracy in the very complex real-world scenarios represented by most urban areas. Joint Urban 2003 (JU03) was a major comprehensive field campaign designed to study the transport and diffusion of pollutants in an urban atmosphere. The emphasis was on threats posed by the release of toxic agents into an urban setting. It represented a highly integrated and multidisciplinary effort that included a major program of meteorological measurements for understanding mean and turbulent flow conditions in the urban boundary layer, a major program of tracer concentration measurements for tracking the dispersion of a pollutant in this environment, and a modeling effort designed to improve the ability to predict the movement of toxic plumes in urban environments using the extensive meteorological and tracer concentration database generated.

The JU03 field study was conducted from June 28 through July 31, 2003 in Oklahoma City. The setting for the study was the southern U.S. high plains and emphasized the effects of the urban canopy and thermal regime (night and day) on plume dispersion. Terrain effects were negligible. A more complete description of this study has been summarized by Allwine et al. (2004) and Allwine and Flaherty (2006). The dispersion of tracer gas from instantaneous puff releases during JU03 has been analyzed by Doran et al. (2007). Other aspects of the JU03 analysis will be published soon (e.g. Burrows 2007; Chan 2007; Flaherty et al. 2007a, b; Nelson 2007; Pardyjak 2007).

It has been established that nocturnal decoupling develops in open terrain above the stable boundary layer (Stull 1988) so its existence in an urban area at night might not be unexpected. Yet it is widely believed that the urban boundary layer is neutral to somewhat unstable day and night (Britter and Hanna 2003; Salmond et al. 2005; Hanna et al. 2006; Harman and Belcher 2006; Offerle et al. 2007). It is thought that mechanically generated turbulence due to the interaction of winds with the elements of the urban canopy and the urban heat island effect are typically sufficient for keeping the boundary layer neutral to unstable around the clock.

This line of reasoning suggests that it cannot be assumed that flow decoupling occurs in the urban nocturnal boundary layer. However, prior work has shown that flow decoupling does develop in the urban boundary layer at low wind speeds (DePaul and Sheih 1986; Britter and Hanna 2003) so the phenomenon has been demonstrated in this setting. What is less clear is how thermal regime (day/night) affects the development of flow decoupling in an urban environment and what influence that might have on the character of plume dispersion.

The analysis of the JU03 tracer data from the continuous releases indicated that nocturnal flow decoupling was a major factor that altered the character of plume dispersion. The focus of this paper will be on demonstrating the presence of nocturnal flow decoupling during JU03 and describing its effects on plume dispersion and the characteristics of the concentration field.

In the discussion to follow, "decoupled flow" will be defined as when interactions between the air mass within the urban canopy and flow above the urban canopy are significantly restricted or cease. Divergence between the overall wind field and the

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direction of plume dispersion is then a possibility and a clear indicator of decoupling. Flow decoupling could also be expressed in somewhat more subtle ways by effects on wind speed profiles, slower plume travel speeds and longer plume decay times, diminished effectiveness of mixing and plume dilution, changes in the character of plume concentration fluctuations, and reduced penetration of flows aloft into the canopy. This paper will focus on these latter phenomena.

2. EXPERIMENTAL DESCRIPTION AND ANALYTICAL METHODS

The experiment was designed to study plume dispersion in an urban environment based upon the release and downwind measurement of a tracer gas in varying atmospheric conditions. The tracer gas measurement aspect of the experiment was supplemented by an extensive suite of meteorological measurements to provide a detailed characterization of the mean and turbulent atmospheric parameters governing the observed tracer distributions (Brown et al. 2004a; Hanna et al. 2006).

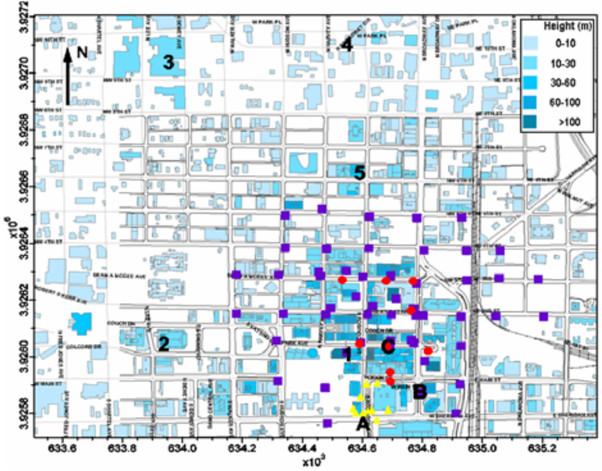

Figure 1. Typical experimental configuration for JU03 [IOP3 tracer measurement array shown: TGA sampler – red ●; Miran sampler - yellow▲; PIGS sampler – purple ■]. Axes are UTM coordinates in meters. Building heights are color coded from light shades of blue (low) to darker shades of blue (high, the CBD). The five PNNL rooftop meteorological stations are numbered 1-5 with #1 denoting the reference wind speed station atop the Oklahoma Tower. The release sites are indicated by letters [A – IOPs 3-7; B – IOPs 2 and 8; C – IOPs 9 and 10].

Ten experiments (Intensive Observational Periods – IOPs), six daytime and four nighttime, were conducted during which the inert tracer gas sulfur hexafluoride (SF_6) was released at a point in the Central Business District (CBD) and measured downwind. A map showing the Oklahoma City urban canopy, tracer release locations for all IOPs, and a representative experimental configuration of the measurement sites in the downtown area is shown in Fig. 1. The tracer releases were executed by the Air Resources Laboratory Field Research Division of NOAA (NOAA ARLFRD). Each IOP consisted of 3 continuous point-source releases lasting one-half hour each and up to 6 instantaneous puff releases.

ARLFRD also collected two tracer concentration data sets, based upon electron capture detection (ECD), at the downwind measurement sites. The first of these was a continuous, real-time data set measured with an array of 9 fixed and one mobile SF_6 Tracer Gas Analyzers (TGAs). The nine fixed TGAs used in the analysis were deployed downwind of the release site at distances exceeding a city block, generally ranging from 175-600 m, more in a few instances. Data from the TGAs were acquired at a rate of 2 Hz. A second set of time-averaged concentration tracer measurements was collected by ARLFRD Programmable Integrating Gas Samplers (PIGS). These bag samplers were deployed at street and rooftop levels throughout the CBD as well as farther downwind on sampling arcs outside the downtown area (not shown on Figure 1). In the CBD, 55 of these samplers were deployed at street level, 10 on rooftops, and 4 in an underground tunnel system. A detailed summary of the tracer release system and ARLFRD SF_6 tracer gas measurement instrumentation can be found in Clawson et al. (2005).

A comprehensive suite of meteorological measurements were made in JU03. Some of the key components are briefly described here. Five meteorological stations were located at the rooftop sites indicated in Fig 1. The building heights for these five stations were (1) 124 m, (2) 31 m, (3) 42 m, (4) 12 m, and (5) 45 m. Wind measurements were made at 3 m above the building height. Pacific Northwest National Laboratory (PNNL) periodically released radiosondes from Wheeler Park, a site upwind from the CBD located a short distance south of the map area shown in Figure 1. PNNL also operated a sodar and radar wind profiler at this site. The whole CBD was covered by a dense surface-based meteorological grid measuring winds, temperature, and radiation on towers at heights ranging from 3-10 m above ground level (AGL). Park Avenue, between Robinson and Broadway, was especially heavily instrumented and included many sonic anemometers on towers as well as some affixed to buildings at various heights. ARLFRD operated a sonic anemometer at the release site.

The present work will emphasize an analysis of the continuous release data. Five daytime (2-6) and four nighttime (7-10) IOPs were analyzed to evaluate what differences in plume dispersion might be attributable to factors relating to atmospheric changes between day and night.

Method limit of detection (MLOD) was defined as the lowest possible concentration that could be determined to be statistically different from zero and was calculated as 3 times the standard deviation of repeated analyses of the lowest possible concentration standard. This was typically a few tens of pptv for the TGAs. Method limit of quantitation (MLOQ) was defined as 10 times the standard deviation. At high concentrations the TGAs were susceptible to two sampling artifacts. The first of these is detector saturation, a condition in which the detector becomes saturated and fails to respond, or only responds weakly in a highly nonlinear manner, to further increases in concentration. The detector saturation limit was nominally about 10,000 parts per trillion by volume (pptv) but could be doubled using a dilution system. The second artifact is called 'railing' and was the result of the signal exceeding the available voltage range. Either artifact resulted in truncation of concentration peaks. Of the 176 tracer time series used in the analysis, 36 (20%) showed evidence of truncation to varying degrees. The MLOD and effect of these artifacts varied according to IOP and the individual sampler.

For the PIGS, bag samples were collected sequentially at programmed times and then analyzed by the ARLFRD Automated Tracer Gas Analysis System (ATGAS) in the tracer analysis facility (TAF). MLOD for the PIGS sampling system was 1 pptv for the samplers used in this analysis with the exception of the bag samplers used in the plume decay analysis (section 3.5). The MLOD for the plume decay samplers was 33 pptv. Concentration peaks measured in the ATGAS facility were not susceptible to truncation.

An additional array of up to 10 continuous Miran real-time analyzers, based on infrared detection, was deployed by Lawrence Livermore National Laboratory in the immediate vicinity of the SF_6 release site at distances ranging from 25-150 m, generally within a city block and mostly within line of sight of the release. These analyzers measured tracer concentrations in the parts per billion by volume (ppbv) range. Data from the Miran samplers were acquired at a rate that varied between instruments and release periods but was commonly about 0.9 Hz.

Most of the analysis of the plume dispersion characteristics will be keyed to time of day (day versus night) and location ('near field' versus 'far field'). For the present purpose the 'near field' will be defined as the tracer concentration field as measured by the Mirans within 150 m of the release site. The 'far field' will be defined as the concentration field as measured by the TGAs (>175 m).

The time series for each TGA and Miran for each continuous half hour release period from each selected IOP was first evaluated for suitability. Records exhibiting critical gaps in the time series, anomalous signals, or suggestions that the tracer signal was absent or very nearly so due to poor sampler placement with respect to the wind direction were excluded from analysis. For the TGAs, data values less than the MLOD were set equal to zero. Values greater than the MLOD but less than the method limit of quantification (MLOQ) were included in calculations. 'Railed' data were also retained although the peak-to-mean ratio (henceforth P:M; the maximum 5-second concentration divided by the mean for the half hour release period) and standard deviation were somewhat reduced in these cases. Removing the railed values, however, did not appreciably affect the overall picture so they were retained since they often represented analyzers located nearest the plume centerline. SF_6 mixing ratios were then converted to concentrations ($\mu g/m^3$) and the resulting time series were block averaged at 5 second intervals. This is approximately equal to the human breathing frequency. In the case of the TGAs, this represented averaging 10 data records. For the Miran analyzers, this was approximated by averaging 5 data records although the data acquisition rate means that the final average actually represented a period slightly longer than 5 seconds.

Measures of plume dispersion and exposure were then calculated from the 5-second time series. These included total integrated exposure (TIE) ($\mu g{*}hr/m^3$) from initial plume arrival to final plume departure; the fraction of the total integrated exposure (TIF) occurring after the release was off; the normalized exposure (the integrated exposure divided by the total mass of SF_6 released); plume arrival times and speeds; the statistical measures of mean, standard deviation, and skewness; the peak-to-mean ratio (P:M); and concentration fluctuation intensity (henceforth CFI; standard deviation of tracer concentration divided by the mean tracer concentration). The mean was calculated for the period from the first plume arrival time until the end of the half hour release period. This was used in the calculation of the P:M because use of the full half hour would have had the distorting effect of reducing the mean due to inclusion of all the leading null concentrations obtained before arrival of the plume at the sampler location.

Plume arrival speeds were calculated by dividing the direct straight line distance between the release and sampler site by the plume arrival time at the sampler. The straight line distance was chosen in lieu of an indirect street-wise distance since it was very difficult to determine with any certainty what the street-wise path to a receptor might have actually been. Furthermore, using the straight line distance directly incorporates the effect of obstructions (e.g. buildings) on the flow and understanding this is an objective of studying dispersion in urban environments. The plume arrival speeds were then divided by a reference wind speed aloft atop the Oklahoma Tower at 124 m height (#1, Fig. 1) to obtain a ratio of plume speed to wind speed (PS/WS). The plume arrival time was selected when the first distinct sustained signal greater than the MLOQ was detected.

TGA data was also analyzed for quantifying the rate of plume concentration decay after the end of a tracer release period. Assuming an exponential decay of the tracer signal, a characteristic peak decay time, τ, can be defined from the relationship $C = C_0 e^{-t/\tau}$. Each TGA time series was examined for concentration peaks that appeared to satisfy the exponential assumption. C_0 was taken to be the concentration associated with the last prominent peak occurring near the time the tracer release was turned off. C was the concentration along the decay curve at about 10% of C_0. The time *t* was the change in time between those two points.

The PIGS data for IOPs 2-10 were also examined from the perspective of plume concentration decay times. One set of PIGS was programmed to collect samples for the two 15-minutes periods covering the release period and then at 5-minute intervals for the half hour after the release had ended (Clawson et al. 2005). The concentration decay was evaluated by determining how long it took for concentrations to reach zero and what fraction of a reference starting concentration was present at five and ten minutes after the release had ended. The maximum integrated concentration measured in a 5-minute post-release sample was taken to be the starting period for calculating plume decay. In a few cases, the second 5-minute post-release sample had a higher concentration than the first and it was selected as the starting period. Then the SF_6 concentrations in the first and second 5-minute periods after the starting period, with concentrations greater than the MLOD, were used to calculate the fraction remaining after 5 and 10 minutes. The times to the first 5-minute zero concentration (less than MLOD) were also calculated.

3. RESULTS

3.1 *Diurnal Character of Plume Concentration Fluctuations and Periodicity*

Representative examples for daytime and nighttime tracer concentration time series are shown in Figs. 2 and 3, respectively. The differences between them are readily apparent. Daytime signals in the far field were characteristically very peaked with large tracer concentration fluctuations, large P:M and standard deviations, and positively asymmetrically skewed probability distributions. Furthermore, the peaks had a definite tendency to occur at regular intervals, i.e. periodically. In contrast, nighttime concentration fluctuations were relatively suppressed and tended to be only weakly periodic, or aperiodic. The tracer typically arrived in a major pulse, lingered with less concentration fluctuation, and then gradually dissipated after the release had ended. The day and night character of the near field time series tended to resemble that of the daytime far field. These differences imply that clean air was being mixed or injected into the plume, or interacting with the plume in a significant way, during the daytime. In contrast, any such interaction was generally more poorly developed at night, at least in the far field.

The suppressed injection or mixing of clean air into the plume at night, and the poorly developed periodicity, is the first line of evidence pointing toward flow decoupling. The mechanisms for sweeping in (e.g. plume meander) or injecting (turbulent bursts from aloft) clean air were better developed during the day than night. The suppressed interaction with winds aloft associated with flow decoupling could explain this.

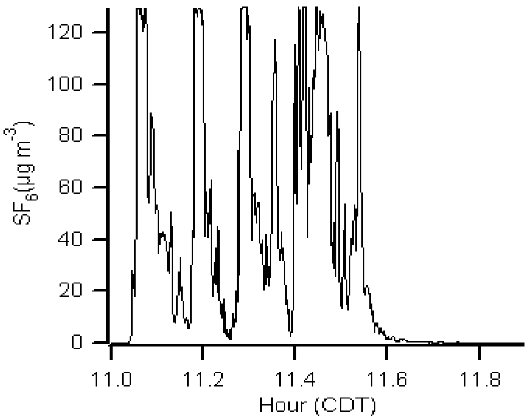

Figure 2. Representative daytime TGA far field SF_6 tracer concentration time series located 175 m from the release site. The tracer release began at 1100 hours and ended at 1130 hours CDT.

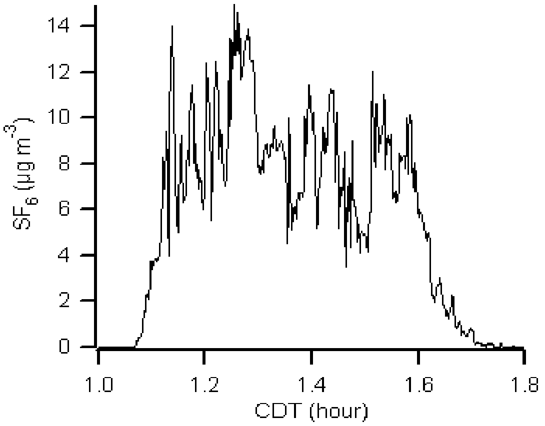

Figure 3. Representative nighttime TGA far field SF_6 tracer concentration time series located 416 m from the release site.

Distinctive periodicity not only occurred more commonly in the daytime far field than the nighttime far field, the spectral power associated with this daytime periodicity was much greater. There was no apparent characteristic frequency, however, with periodicities exhibiting the most power commonly in the range of 6-16 minutes. Near field periodicity, for both day and night, resembled those for the daytime far field although there tended to be a greater contribution from higher frequencies. While it cannot be considered characteristic, when multiple frequencies were present, it was sometimes the case that they were approximately harmonics of the lowest frequency.

3.2 *Attenuation of Canopy Wind Speeds*

Figure 4 is a plot of the mean scalar wind speeds for four stations located in the downtown area near the CBD on buildings ranging in height from 12-45 m against the scalar wind speed at the Oklahoma

Tower (station #1) at 124 m in the CBD. All of these station locations are indicated in Fig. 1. The four lower elevation stations to the west or north (downwind) of the CBD can be considered to have been embedded within the flow of the upper urban canopy while the Oklahoma Tower station was located well above the canopy. This shows that the magnitude of the wind speeds within the upper portion of the urban canopy were approximately equal in magnitude to the wind speeds above the urban canopy during the daytime. At night, however, wind speeds at the Oklahoma Tower were more than double the wind speeds at the lower heights. This is another line of evidence suggestive of flow decoupling.

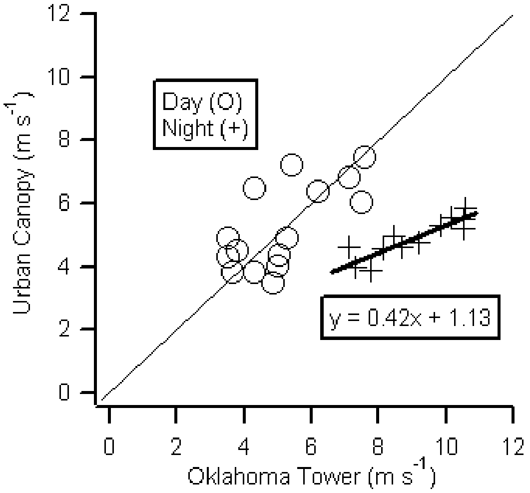

Figure 4. Plot of scalar wind speeds at rooftop sites within the urban canopy versus the scalar wind speed on top of the Oklahoma Tower (above the canopy at 124 m height) for the half-hour continuous release periods, IOPs 2-10. The daytime results cluster around a line with a slope of unity. The nighttime results cluster around the regression line with the slope and intercept shown.

3.3 *Wind Speed Profiles*

The sodar and wind profiler operated by PNNL at Wheeler Park, a short distance south (upwind) of the map area, measured the approach flow to the downtown area. One of the questions raised in the analysis of Fig. 4 was whether the wind speeds associated with the overall wind field at night were actually consistently greater than the daytime wind speeds as the graph suggests. Representative wind profiles for daytime and nighttime cases are shown in Figs. 5 and 6, respectively. These figures suggest this was not necessarily the case.

Low level nocturnal jets (LLJ) have been identified as a common phenomenon over the southern plains of the U.S. during spring and summer months (Zhong et al. 1996; Parish et al. 1988; Savijarvi 1991; Jiang et al. 2007; Djuric 1981; Walters 2001; Banta et al. 2006; Frisch et al. 1992). While debate continues on a complete explanation for their formation, there is general agreement that frictional decoupling plays a very important role. During the day well-developed turbulence couples the flow with the surface resulting in frictional drag that retards wind speeds near the surface to subgeostrophic. When turbulence decays at night the frictional drag on the wind is also relaxed and the wind speed can become supergeostrophic above the surface. This acceleration results in the LLJ formation. LLJ were reported as being very common during JU03 (Lundquist and Mirocha 2006; Wang et al. 2006). They almost certainly explain the results shown in Figures 5 and 6 and suggest that the meteorological station on the Oklahoma Tower was influenced by the lower portions of the LLJ at night.

Peak LLJ wind speeds were typically at about 400-500 m AGL. The LLJ began decaying as turbulence began to increase the following morning but it was common to see it persist to some degree until late morning while gradually lifting from the surface. The wind speed peak at 1100 CDT at about 1000 m AGL is an example of this.

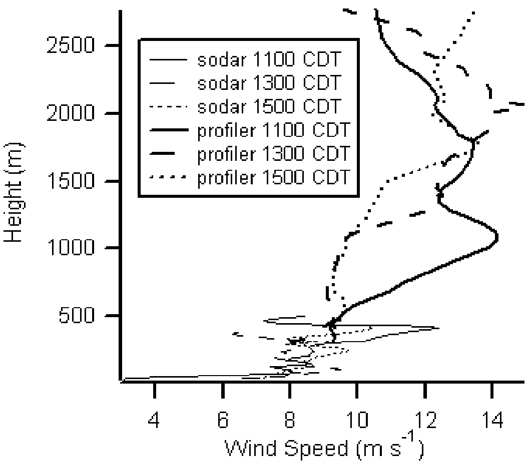

Figure 5. Daytime wind speed profiles from the sodar and radar wind profiler at Wheeler Park located upwind from CBD, IOP 3.

The existence of a LLJ explains the high nighttime wind speeds observed at the Oklahoma Tower relative to the lower stations. There is no evidence to indicate that nighttime winds, excluding the LLJ effects, were greater than daytime winds. In fact, the profiler data suggest that the wind speeds above the LLJ during the morning were actually somewhat greater than the nighttime wind speeds above the LLJ, at least for the representative cases shown. Furthermore, the mere presence of a LLJ also implies that the approach flow was already decoupled before it even arrived over the CBD since a LLJ is direct evidence of frictional decoupling. It is not clear whether the interaction of the LLJ with the CBD urban canopy would have acted to further decouple the flow or perhaps contributed to generating bursts of turbulence that influenced the tracer concentration field (Lundquist and Mirocha 2006; Banta et al. 2002; Coulter and Doran 2002; Mahrt and Vickers 2002). Lidar measurements during

JU03 showed that the winds decelerated and turned as much as 10 degrees as flow approached the CBD (Calhoun et al. 2006). Tetroon experiments have found similar results over other urban areas (Angell et al. 1971). The daytime JU03 continuous tracer releases were generally conducted in the subgeostrophic conditions shown in Fig. 5. The nighttime continuous releases were generally conducted in the supergeostrophic conditions shown in Fig. 6.

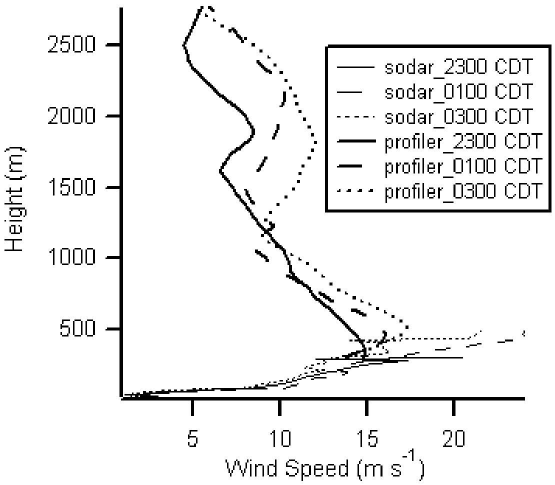

Figure 6. Nighttime wind speed profiles from the sodar and radar wind profiler at Wheeler Park located upwind from CBD, IOP 8.

3.4 *Plume Transport Speeds and Decay Times*

Differences between day and night were also observed in measures of plume transport speed and concentration decay after a tracer release had ended. Typically, tracer plumes arrived sooner and dissipated more quickly in the daytime than the nighttime. Measurable quantities of tracer (>MLOD) sometimes persisted in the far field for almost an hour after the release had ended. This lingering of low level plume concentrations in the far field was most common at night but sometimes occurred during the day as well.

Some of the differences between day and night that were observed in the far field TGA data are shown in Fig. 7. This graph shows results for IOPs 2-10 for all TGA analyzer data satisfying quality control criteria. For the decay time τ, all such records were used provided that a prominent concentration peak existed near or after the termination of the release from which a calculation could be made. The last peak was used for the calculation if more than one such peak was present. For TIF and PS/WS only those cases were used that were considered to have been significantly influenced by the plume. The criterion for this was excluding those analyzers near the periphery of the plume with total normalized exposure values less than 5% of the maximum observed for that IOP (i.e. nominally the plume centerline values).

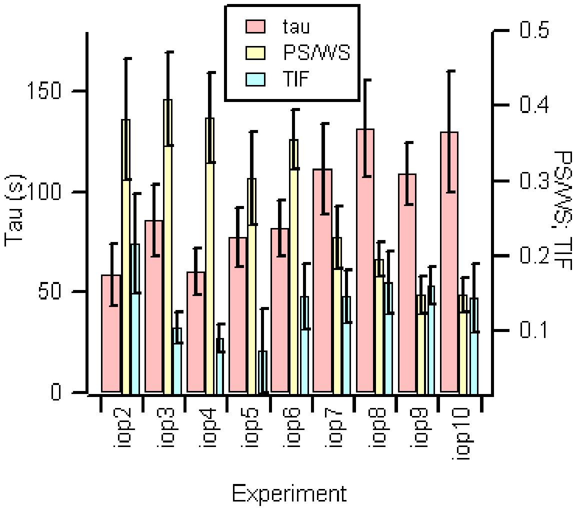

Figure 7. Characteristic exponential decay times, fraction of the total integrated exposure measured post-release (TIF), and ratio of plume arrival speeds to wind speed above the urban canopy (PS/WS) for the far field for IOPs 2-10. Daytime IOPs were 2-6; nighttime 7-10.

One of the more apparent features of this graph is the faster plume arrival speeds as a fraction of the reference wind speed aloft (Oklahoma Tower, Fig. 1, #1) during the daytime. The key point here is that the lower ratios of plume speed to the reference wind speed were consistent with nocturnal flow decoupling. Faster wind speeds aloft were more readily able to penetrate to the surface and transport the plume during the day than at nighttime. The total population of plume speed data was combined and sorted into day and night. The null hypothesis that the ratio of plume speed to wind speed aloft were equal day and night was rejected at $\alpha = 0.001$, showing a clear difference between day and night.

It is also interesting to note that the lowest values of the ratio of plume speed to wind speed were associated with the nighttime IOPs 9 and 10. The release location for these IOPs (point 'C') was deep in the Park Avenue street canyon oriented approximately perpendicular to the prevailing southerly flow (Fig. 1). In contrast, the release for IOP7 was located in a relatively open area (botanical garden, point 'A') and had the largest plume speed to wind speed ratio for the nighttime IOPs. This implies that canopy elements played a role in retarding the plume speed as might be expected.

Another obvious feature of Fig. 7 was the longer characteristic exponential decay times (τ) for nighttime plumes. The results shown are for the decay times associated with the dissipation of the last major tracer peak occurring at the close of the tracer release period. Peaks often decayed much faster than indicated by the averages shown. This was especially true for the daytime far field (e.g. Fig. 2) and the near field at any time. In other cases, a nonzero tracer signal would sometimes reappear sporadically after extended period(s) of null concentration. This was especially common for some of the nighttime cases. Like the plume speed data, the decay time data were sorted into day and night populations. The null hypothesis that the day and night plume decay rates were equal was rejected at α = 0.001. The point here is that winds capable of more quickly flushing out the tracer plume were suppressed due to flow decoupling.

The differences between day and night for TIF shown in Fig. 7 were more ambiguous than the decay time and plume speed results. There was a suggestion of a tendency for higher nighttime TIF values, excluding IOPs 2 and 6. While it is not readily apparent from the graph, a hypothesis test using the null hypothesis that the combined day and night TIF populations were equal was rejected at α = 0.05. TIF values in the near field were also higher during the nighttime than their daytime counterparts.

The results of the PIGS plume decay time analysis are shown in Fig. 8. The distinction between day and night is again apparent with plumes having clearly persisted longer during nighttime IOPs.
The 5 and 10 minute post-peak concentration fractions, measured during the successive 5-minute integrated samples following the associated peak reference concentration of the post-release period, were also higher at night than during day. All of these PIGS observations are consistent with nocturnal flow decoupling.

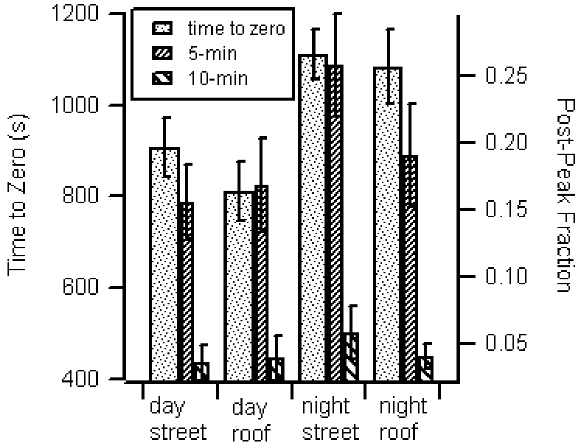

Figure 8. Mean PIGS concentration decay times (time to zero) and fraction of the maximum 5-minute post-release concentration measured later at 5 and 10 minutes for IOPs 2-10.

3.5 *Vertical Mixing*

It was just noted that there are differences between the rates of tracer concentration decay after termination of the releases, between daytime and nighttime (section 3.4). No mention has yet been made, however, about how tracer concentrations might vary between street and rooftop levels during the release period and what that might imply about dispersion in the vertical.

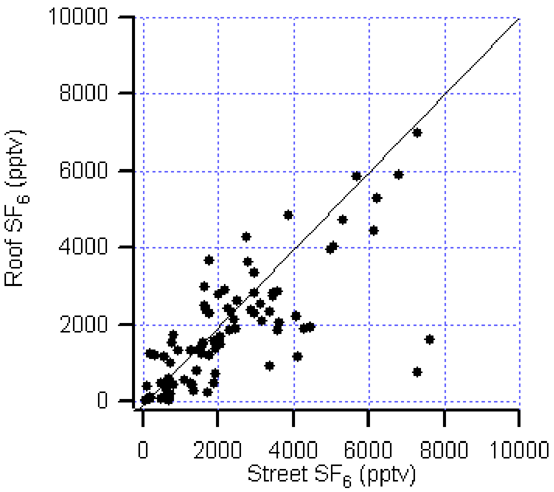

Figure 9. Comparison between all nonzero one-half hour average SF_6 measurements less than 10,000 pptv for vertically collocated street and rooftop PIGS for daytime IOPs 2-6.

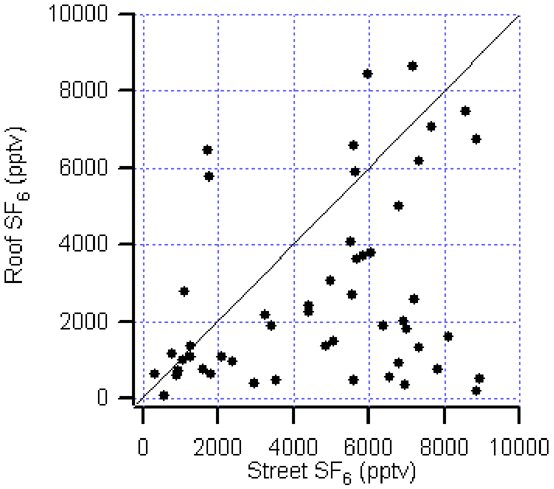

Figure 10. Comparison between all nonzero one-half hour average SF_6 measurements less than 10,000 pptv for vertically collocated street and rooftop PIGS for nighttime IOPs 7-10.

Comparisons of integrated tracer concentrations measured by approximately vertically collocated street level and rooftop PIGS in the downtown area are shown in Figs. 9 and 10 for daytime and nighttime cases, respectively. A small fraction of the data points with concentrations greater than 10,000 pptv were excluded to show greater detail in the lower concentrations. The results show a much better correlation between surface and rooftop tracer concentrations during the daytime implying strong vertical mixing (and coupled flow). In contrast, there was no evidence of a correlation between surface and rooftop tracer concentrations at nighttime implying poorly developed vertical mixing (and flow decoupling).

3.6 *Concentration Fluctuation Intensities, P:M ratios, and Canopy Effects*

An overall summary of plume concentration fluctuations as a function of day, night, and canopy geometry is shown in Fig. 11. This graph shows results for IOPs 2-10 for all TGA analyzers that were (1) considered to have been significantly influenced by the plume and (2) whose location could be reasonably determined to be either in an open and relatively unsheltered position within the canopy (op), given the southerly wind direction, or in a more sheltered position such as deep within a street canyon (sc). The idea behind (2) is that the sheltering effects of canopy elements might be expressed as variations in tracer concentration.

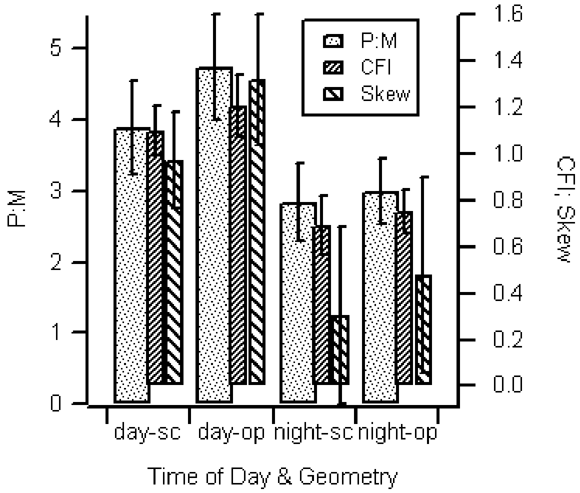

Figure 11. Mean daytime and nighttime P:M, CFI, and skewness values for TGA far field analyzers located in open positions more susceptible to wind penetrating the urban canopy (op) or at mid-block locations within street canyons mostly protected from winds penetrating the canopy (sc). Plume outliers were excluded. Error bars are 90% confidence intervals.

The first condition was satisfied by excluding outlier values from those analyzers that lay at the periphery of the plume, as previously described. For the second condition those TGAs that were positioned where there was apparently relatively little in the way of canopy obstructions to significantly affect the approach flow were designated 'open' (op). This category mostly represents analyzers sited at street intersections but also includes some analyzers sited in streets aligned with the prevailing wind direction. Those TGAs that were positioned mid-block within street canyons clearly aligned transverse to the wind direction were designated as 'street canyon' (sc). These analyzers were clearly sheltered from the wind and buildings greatly altered the approach flow to these TGAs. TGAs whose classification was less certain were excluded. Examples of this include analyzers positioned near an intersection but just around the corner of a building that could offer it some shelter from the wind (i.e. at the end of a street canyon). A wind tunnel study by Kastner-Klein and Rotach (2004) provides a further basis for attempting this analysis. They identified two regions within the urban canopy: (1) street intersections (analogous to 'op') characterized by higher mean wind and turbulent velocities and (2) areas between buildings characterized by lower velocities (i.e. 'sc').

Figure 11 shows that P:M, concentration fluctuation intensity CFI, and skewness were all higher during the daytime than nighttime for JU03. This is confirmed by hypothesis testing that concludes that the daytime populations of P:M, CFI, and skewness are greater than the nighttime values. The null hypothesis that they were equal was rejected at $\alpha = 0.005$. The inference that can be drawn is that winds and turbulence were more readily able to penetrate the urban canopy during the daytime, bringing frequent large incursions of tracer-free air to interact and mix with the plume and cause large concentration fluctuations (e.g. Fig. 2). The characteristic large daytime concentration fluctuations and periodicity were then largely related to shifts in direction of the ambient wind (i.e. plume meander) or, perhaps, turbulent injections of uncontaminated air from aloft. In contrast, nighttime flow decoupling conditions restricted the injection into and mixing of clean air with the plume resulting in suppressed concentration fluctuations (e.g. Fig. 3). Again, this is entirely consistent with flow decoupling and the other lines of evidence already presented. Bear in mind that Fig. 11 contains some "railed" tracer concentration peaks so some of the P:M, CFI, and skewness values were actually higher than shown. Railing was more common during daytime IOPs than nighttime IOPs.

While the daytime results for 'op' and 'sc' were similar, there was a hint that the concentration fluctuations for 'op' were somewhat greater than for 'sc'. The null hypothesis that the daytime and nighttime populations for P:M, CFI, and skewness were equal was accepted for $\alpha = 0.1$ suggesting the differences might not be statistically significant. Similarly, there was a hint that nighttime concentration fluctuation results for 'op' were greater than those for 'sc' but again the differences may not have been statistically significant. These results imply that there was sufficient mixing during daytime to minimize the canopy effects (i.e. sc vs. op) on the concentration field. While the nighttime 'op' and 'sc' results were also similar, it was already observed that the urban canopy apparently had some influence on plume speeds at night. Nevertheless, the consistency in the concentration fluctuation statistics (i.e. 'op' ≈ 'sc') together with the preponderance of the other lines of evidence suggests canopy effects at night were subordinate to the effects of the decoupled flow field and relative lack of turbulent mixing. At night the analyzers at the 'op' sites were shielded from the effects of turbulent bursts and/or winds penetrating from aloft almost as well as analyzers at 'sc' sites. Of course the possibility that the urban canopy itself might have contributed to the onset and intensity of the nocturnal flow decoupling should still be recognized.

The possible effect of the canopy on the decay time τ was also examined from the perspective of 'op' and 'sc' TGA location. The TGA data was classified into four populations: day-sc, day-op, night-sc, night-op. The mean decay times for these were 77.2, 66.0, 123.7, and 101.3 seconds, respectively. The null hypothesis that the day-sc and day-op populations were equal was not rejected at $\alpha = 0.1$ suggesting that the difference between those two populations is probably negligible and statistically insignificant. The null hypothesis that the night-sc and night-op populations were equal was rejected for $\alpha = 0.05$ indicating a significant difference between these two populations. This implies that the sheltering effect on plume dispersion by street canyons relative to more open areas was probably greater during the nighttime than daytime. It was noted earlier in section 3.4 that the release location in a street canyon for IOPs 9 and 10 appeared to have retarded the PS/WS ratios for these nighttime cases.

4. DISCUSSION

At the outset it was stated that there was evidence for nocturnal flow decoupling during JU03. The evidence for flow decoupling came in the form of effects on wind speed profiles, slower plume travel speeds and resultant longer plume decay times, diminished effectiveness of vertical mixing and plume dilution, changes in the character of plume concentration fluctuations, and suppressed penetration or injection of clean air into the plume within the canopy. We will now examine how different factors might have influenced the onset and intensity of flow decoupling in JU03 and what effects these might have had on the plume dispersion phenomena listed.

The first factor is thermal regime, i.e. the air temperature and solar insolation differences between day and night. There was no evidence in the air temperature gradient data to indicate that nocturnal stable conditions ever developed within the urban canopy of the CBD in JU03. This is consistent with the conclusions of other researchers who have broadly argued that enhanced roughness elements, the higher wind speeds typical of tracer experiments, and urban heat island factors combine to ensure neutral to weakly unstable conditions within urban canopies, even at night (Britter and Hanna 2003; Salmond et al. 2005; Hanna et al. 2006; Harman and Belcher 2006; Offerle et al. 2007). Ramamurthy et al. (2004) and Nelson et al. (2004) reported small positive sensible heat fluxes throughout the night from measurements made in the Park Avenue street canyon during JU03. Others have asserted that near neutral conditions were present during both the day and at night based on a modeling approach (Chan and Lundquist 2006). These results indicate that urban nocturnal flow decoupling is tied to more than simple considerations of atmospheric stability only.

The detailed work of Nakamura and Oke (1988) indicates that sharp temperature gradients develop in an urban street canyon during the day and lead to significant instability and vertical mixing via the classic cross-canyon vortex. By late afternoon the vortex circulation reaches a maximum and vertical mixing has eliminated most of the temperature gradients resulting in near neutral stability in the canyon. At night, however, even though there might be sufficient heat in the urban canyon to generate a small positive sensible heat flux, temperature gradients are small, buoyant turbulence and mixing is suppressed relative to daytime, and thermally-generated vertical motion is limited. In the near absence of buoyant turbulence there might be insufficient mechanically-driven turbulence within the urban canopy to prevent the flow from decoupling.

This result points toward flow decoupling being more directly linked to the level of turbulent kinetic energy (TKE) which increases in response to daytime heating. High TKE and strong vertical mixing will generate rising eddies and turbulent interactions that will act as a frictional drag on the flow above the canopy. This process will promote coupling of flow in the canyon with flow above rooftops as well as promote vertical mixing of the tracer plume as was observed in the daytime JU03 IOPs. It was also pointed out that the nocturnal LLJ, a feature of all the nighttime IOPs in JU03, are at least partly attributable to the decay of turbulence and are direct evidence of frictional decoupling of the flow. Finally, Kastner-Klein and Clark (2004) found that the magnitudes of nighttime wind speeds and TKE in the Park Avenue street canyon experiment were about one-half those of the daytime for the entirety of JU03. This is also consistent with the longer nighttime plume concentration decay times. All of the JU03 results are consistent with daytime surface heating and the associated turbulence being very important to the maintenance of coupled flow within an urban canopy. In the absence of surface heating, turbulence intensity declines and nocturnal flow decoupling follows.

A second factor to consider in the development of flow decoupling is the ambient wind speed. It has been reported that at lower wind speeds there is a decoupling of flow within an urban canyon from flow above the canyon (DePaul and Sheih 1986; Britter and Hanna 2003) at a rooftop wind speed threshold of about 1.5-2 m s^{-1}. It can only be speculated as to whether this threshold would be applicable to the Oklahoma City urban canopy during the day since there was no evidence for flow decoupling during the daytime experiments. The approach flows were well in excess of this threshold for all IOPs during JU03. Allowing for the LLJ and effects on the wind speed profiles due to the observed decoupling, the wind speeds at night were comparable in magnitude to the daytime wind speeds. However, the development of flow decoupling during the nighttime experiments indicates that thermal regime is of much greater importance than wind speed in determining the onset of flow decoupling.

A third factor to consider in the development of flow decoupling, and its influence on the plume concentration field and transport, is the effects of the urban canopy itself. The angle of the approach flow is an important consideration in determining the urban canopy effects. Wind direction relative to the street canyon orientation has been found to be critical to understanding the turbulent features present, how they relate to spatial variability of turbulence, and the development of intermittency, notably for JU03 (Brown et al. 2004b; Kastner-Klein and Clark 2004; Ramamurthy et al. 2004).

Another point of discussion is the possible relationship(s) between turbulent features and the intermittency or variability of the tracer plume concentration fields observed in JU03. Nelson et al. (2004) found intermittent, periodic behavior in turbulent spectra for JU03 although no single characteristic frequency was identified. The discovery of periodicity in the turbulent spectra for JU03 is consistent with the observations of periodicity in SF_6 concentrations (e.g. Fig. 2). The enhanced concentration variability and periodicity during the daytime is then simply the consequence of greater flow coupling. Coupled flow would permit flow aloft to penetrate to street level and enhance the possibility that plume meander would influence the observed concentration field. Coupled flow would also enhance the possibility of turbulent bursts and sweeps of clean air from aloft. Either of these could be expressed as large fluctuations and periodicity in the tracer concentration signal. The relatively damped fluctuations and poorly developed periodicity observed at nighttime suggests these mechanisms were not as important at night in the flow decoupled regime.

Other ideas to consider in the context of identifying possible mechanisms for explaining the variability of the tracer concentration results include intermittent turbulent bursts at night associated with the LLJ (e.g. Banta et al. 2002; Coulter and Doran 2002; Mahrt and Vickers 2002), slight changes in the angle of the approach flow resulting in alterations to the concentration and vortex fields (including vortex shedding), and turbulent intermittency associated with the development of rooftop level shear layers (Britter and Hanna 2003; Nelson et al. 2004; Ramamurthy et al. 2004; Louka et al. 2000).

It is not clear what effect intermittent turbulent bursts associated with the LLJ might have had on tracer concentrations at the surface. As is clear by now, concentration variability at night was less than during the day during JU03 so it might be argued that this was not an important mechanism. However, it is also possible that the observed concentration fluctuations at night would have been even less without this source of turbulence.

5. CONCLUSIONS

Some specific conclusions can be drawn from this research:

- Flow decoupling develops within the urban boundary layer at night in response to the thermal regime.
- Flow decoupling can be expressed as alterations to the wind speed profile as well as by slower plume travel speeds and longer plume decay times, diminished effectiveness of mixing and plume dilution, changes in the character of plume concentration fluctuations, and reduced penetration of clean air aloft into the canopy.
- The role of wind speed in initiating urban flow decoupling is secondary to thermal regime. Turbulence decay at night results in diminished frictional coupling between air within the urban canopy and air aloft.
- Tracer concentration signals in the near field usually exhibited large, often periodic fluctuations with large P:M and CFI, both day and night.
- Tracer concentration signals in the daytime far field usually exhibited large, often periodic fluctuations with relatively large P:M and CFI.
- Tracer concentration signals in the nighttime far field tended to exhibit much smaller, mostly aperiodic fluctuations and smaller P:M and CFI.
- In general, tracer plumes arrived sooner and dissipated more quickly in the daytime than the nighttime. Characteristic exponential peak tracer concentration decay times were less during the day than night.

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